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USE OF WATER VAPOUR PERMEABLE FABRICS IN TENTS (U)

by

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ABSTRACT

The usefulness of a tent used in cold weather depends upon, among other things, the condensation of water vapour on the tent walls as this condensate can wet occupants' insulating garments, increase the tent weight and increase the tent's packed volume. In this report, the heat and moisture transport across a single fabric layer as might occur in a tent is studied by means of a simple, numerical model. The effects of water-vapour permeability of the fabric, interior air temperature and relative humidity and the ambient temperature on the condensation rate within the tent are examined. It was found that small decreases in the water-vapour permeability of the fabric layer can result in large increases in the condensation rate at the wall. Reducing the interior tent temperature or relative humidity can significantly reduce the condensation rate. The results indicate that a substantial portion of the water vapour within a very humid tent atmosphere escapes through the tent walls in all but the coldest ambient conditions for fabrics with low water-vapour resistance. Some of the advantages and disadvantages of using a single vapour permeable, waterproof fabric in place of more conventional arrangements with a permeable tent wall covered with an impermeable fly-sheet are discussed.

RESUME

L'utilité d'une tente utilisée par temps froid dépend, entre autre, de la condensation de vapeur d'eau sur les parois de la tente. Cette condensation peut dégoutter sur le vêtement isolants des occupants, augmenter le poids de la tente et augmenter son volume d'empaquetage. Dans ce rapport, le transfert de chaleur et d'humidité à travers une seule couche de matériel, comme dans le cas d'une tente, sont étudiés par l'entremise d'un modèle numérique simple. Les effets de perméabilité à la vapeur d'eau du tissu, de température intérieure et d'humidité relative et de température ambiante sur the taux de condensation à l'intérieur de la tente sont examinés. Il fut trouvé que de petites réductions dans la perméabilité à la vapeur d'eau de la couche de tissu peut résulter en une augmentation importante du taux de condensation sur la paroi. Une réduction de la température intérieure ou de l'humidité relative de la tente peut réduire le taux de condensation de façon significative. Les résultats indiquent qu'une portion substantielle de la vapeur d'eau dans une tente humide, s'échappe à travers les parois de la tente toutes conditions, sauf les plus froides, pour les tissus de basse résistance à la vapeur d'eau. Une discussion est faite des avantages et désavantages de l'utilisation d'un seul tissu perméable à la vapeur, imperméable à l'eau au lieu de l'arrangement conventionnel d'une tente perméable couverte par une toile imperméable.

EXECUTIVE SUMMARY

Tents have been providing man with shelter from the environment for thousands of years but their design and materials have changed little until the development of man-made materials such as nylon fabrics and carbon-fibre poles. Reductions in weight, volume and construction costs have been the prime reason for the shift to man-made materials, however, the search for a more comfortable shelter is undoubtably in the back of every tent designers mind. To this end, designers and users are exploring the use of water-vapour permeable, water-proof fabrics as tentage fabric.

In cold weather, large amounts of water vapour are released into a tent's atmosphere when liquid fuel stoves are used for cooking and heating. In addition, there is water vapour respired by the tent occupants. This makes the tent micro-climate very humid. When the humid air comes in contact with cool surfaces, such as the tent walls or floor, condensation, or sublimation in very cold environments, occurs. This condensate can then be absorbed into clothing or sleeping bags, impairing their insulating qualities. The condensation or frost can also degrade the tent's performance by increasing its weight and increasing the material stiffness which results in a larger packed volume. Thus, it is desirable to be able to predict where water vapour will go in cold-weather tents in order to minimize potential condensation problems by proper design.

This report presents a simple, numerical model of heat and water-vapour transport across single tent walls. Some typical cases are reported for various wall materials and a discussion of the implication of the results is included.

The study indicates that vapour-permeable, water-proof fabrics can be used for tents so that a fly-sheet is unnecessary, thereby reducing the overall weight of the tent. Since these fabrics generally have higher water-vapour diffusion resistance than uncoated fabrics, their use will increase the amount of condensation on the inside tent wall over similar tents of uncoated fabrics in most cases.

Since many water-proof, vapour permeable fabrics have significant resistance to the diffusion of air, care must be taken to select materials which do permit diffusion. The user must be made aware of the potential hazards which can arise unless adequate ventilation is maintained.

Elimination of the fly-sheet does present some other problems, especially for military applications. Degradation of the tent materials due to solar radiation may occur more quickly and the degree of camouflage against visible and infra-red radiation will be reduced in many situations.

In conclusion, the designer and the user must decide whether advantages of a vapour-permeable, water-proof tent without a fly-sheet over a conventional fabric tent with an impermeable fly-sheet are greater than the disadvantages. The savings in weight achieved by eliminating the fly-sheet must be evaluated against the disadvantages such as increased condensation within the tent, shorter material life-span, lower thermal insulation and reduced camouflage capability.

1.0 INTRODUCTION

Tents have been providing man with shelter from the environment for thousands of years but their design and materials have changed little until the development of man-made materials such as nylon fabrics and carbon-fibre poles. Reductions in weight, volume and construction costs have been the prime reason for the shift to man-made materials, however, the search for a more comfortable shelter is undoubtably in the back of every tent designers mind. To this end, designers and users are exploring the use of water-vapour permeable, water-proof fabrics as tentage fabric.

In cold weather, large amounts of water vapour are released into a tent's atmosphere when liquid fuel stoves are used for cooking and heating. In addition, there is water vapour respired by the tent occupants. This makes the tent micro-climate very humid. When the humid air comes in contact with cool surfaces, such as the tent walls or floor, condensation, or sublimation in very cold environments, occurs. This condensate can then be absorbed into clothing or sleeping bags, impairing their insulating qualities. The condensation or frost can also degrade the tent's performance by increasing its weight and increasing the material stiffness which results in a larger packed volume. Thus, it is desirable to be able to predict where water vapour will go in cold-weather tents in order to minimize potential condensation problems by proper design.

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2.0 MATHEMATICAL MODEL

The flow of heat and moisture was modeled using an electrical circuit analogy as shown in Figure 1. This technique provides a simple, quick means of obtaining an estimate of the flow of heat and mass. It does, however, obscure some of the physics of the real problem as transport through moving air involves both conduction of heat (diffusion of water vapour) as well as convection. Convection is a characteristic of the flow field and resulting transport should be characterized by a heat transfer coefficient rather than a resistance which implies a physical property of the fluid. It is often mathematically more convenient to use a resistance instead of a heat transfer coefficient which is the reason for its use in this paper.

2.1 Modelling Heat Transfer

Heat transfer by conduction between two points can often be written as the temperature difference, ΔT, between those points divided by the thermal resistance of the intervening medium:

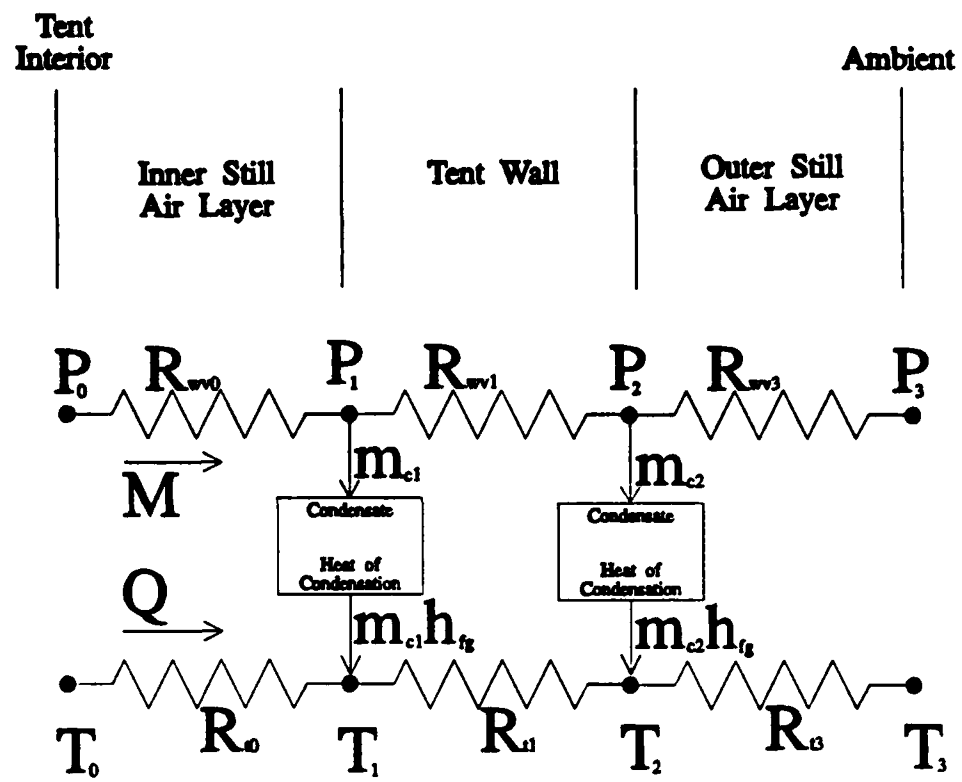

Figure 1. Problem definition and its electrical circuit analogy. Heat and moisture flow from the warm, humid tent interior on the left through the inner still air layer, the tent fabric and the outer still air layer to the cold, humid ambient air on the right. The model restricts condensation to the inner and outer surfaces of the fabric only.

$$Q_c = \Delta T / R_c \qquad (1)$$

where the conductive thermal resistance, R_c, is defined as:

$$R_c = L_c / k \qquad (2)$$

with L_c being the thickness and k the thermal conductivity of the conducting layer.

The conductive heat transfer across the thermal boundary layer of a slowly moving stream of air has been found to be approximately equivalent to that across a still air layer with a thickness of 5 mm [Farnworth 1983]. The effects of convection are largely ignored or at most represented by reducing the thickness of the still air layer.

In most practical problems, heat transfer involves both a conductive and a radiative component. Radiative heat transfer between surfaces, Q_r, depends upon the fourth power of the surface temperatures, however, for small temperature differences, this may be approximated by a linear temperature difference:

$$Q_r = \epsilon \sigma (T_1^4 - T_2^4) \approx 4 \epsilon \sigma T_a^3 \Delta T \tag{3}$$

where T_a is the average temperature between the two surfaces. The surface emissivity, ϵ, of clean, dry fabrics is typically between 0.5 and 0.85 [Cain 1986], however, dirty or wet fabrics will have emissivities close to unity. The symbol, σ, represents the Stefan-Boltzmann constant ($5.67\text{x}10^{-8}$ W/m^2K^4). From this, a resistance to thermal radiation can be defined as:

$$R_r = 1 / (4 \sigma T_a^3) \tag{4}$$

where an emissivity of one has been assumed for simplicity.

The total heat flow, Q_T, across a layer of air can thus be determined, approximately, knowing the temperature difference and the resistance to both conductive and radiative heat flow:

$$Q_T = \Delta T (1/R_c + 1/R_r) = \Delta T/R_t \tag{5}$$

Fabric thermal resistances are usually small since most fabrics are thin. The thermal conductivity of a wide range of woven fabrics is typically between 0.03 and 0.05 W/mK [Fourt 1970]. Insulating materials such as fibrous battings are quite different, having larger thermal resistances derived from entrapped air and from reduced radiative heat transport. The thermal resistance of fabrics can be calculated as per equation 2 by using the fabric thickness and thermal conductivity.

2.2 Modelling Water Vapour Transfer

The flow and resistance to flow of water vapour can be described in an analogous manner to heat transfer, although, there is no corresponding component to radiative heat transfer. The mass flow rate due to diffusion of vapour in a fluid between two points can often be written as the difference between the vapour pressures at those points divided by the diffusion resistance of the intervening medium:

$$M = \Delta P_v / R_{wv} \tag{6}$$

If the vapour and the fluid can be treated as ideal gases, the diffusion resistance can be simply related to the diffusivity, D, by:

$$R_{wv} = L_D R T / m D \tag{7}$$

where L_D is the thickness of the diffusion layer, R is the Universal Gas Constant (8.314 N.m/gmole.K), T is the mean absolute temperature of the diffusion layer and m is the molecular weight of the diffusing species (18 g/gmole for water vapour). The water-vapour diffusivity is a known function of temperature and pressure [List 1951; ASHRAE 1972]:

$$D/D_o = (T/T_o)^n (P_o/P) \tag{8}$$

where D_o is the diffusivity (0.226 m^2/s) at the reference conditions (T_o=273.16 K) and atmospheric pressure (P_o = 101.3 kPa) and n is a constant (n≈1.81).

The equivalent thickness of the diffusion layer for the transport across the boundary layers can be estimated from that found for the equivalent thickness of the thermal resistance layer or still air layer. It has been found [Rosenhow 1961] that the mass transfer coefficient, h_D, and the heat transfer coefficient, h_t, can be related by:

$$h_D/h_t = (Pr/Sc)^{2/3} / \rho c_p \tag{9}$$

where Pr is the Prandtl number and Sc is the Schmidt number, both of which are known functions of physical properties, ρ is the fluid density and c_p is its specific heat. The mass transfer coefficient is defined as the mass diffusivity divided by the diffusion length:

$$h_D = D / L_D \tag{10}$$

and the heat transfer coefficient is defined as the thermal conductivity divided by the conducting length:

$$h_t = k / L_c \tag{11}$$

By using equations 9 to 11 the ratio of the two length scales can be shown to be:

$$l_c/l_D = (Pr/Sc)^{2/3} (k/\rho c_p D) \tag{12}$$

When typical values for air and water vapour are substituted into the right-hand side of equation 12, it is found that:

$$l_c/l_D = 0.9 \approx 1 \tag{13}$$

Thus, as a first approximation, the length scale for mass diffusion across air layers will be the same as that used for thermal conduction.

The water-vapour resistance of fabrics can vary significantly with a number of variables. Fabric construction, thickness, fibre type [Whelan 1955] and relative humidity [Osczevski 1989] can all be important. Some typical values for several fabrics are given in Table 1. For historical reasons, the water-vapour resistance of fabrics is frequently quoted in an equivalent thickness of still air. To calculate the water-vapour resistance, equation 7 is used with the equivalent thickness of still air used as the thickness of the diffusion layer.

When the temperature of the air or a surface drops below the dew point, condensation of the water vapour to a liquid occurs. This is an exothermic process and the thermal energy released is called the latent heat of condensation. The rate at which heat is evolved is equal to $h_{fg}m_c$, where h_{fg} is the enthalpy of condensation and m_c is the condensation rate. When problems involve the transport of both heat and moisture, the processes are interdependent and allowance must be made for condensation (or evaporation) with its accompanying local heat flux.

2.3 Solution Algorithm

The solution algorithm used in this report assumes steady state conditions. The unknowns which are of interest are the conditions at the inner and outer surfaces of the fabric wall (temperature and rate of condensation) as well as the rate of water-vapour transport from the tent through the walls. Applying

Table 1. Water-vapour Resistances of some common fabrics [Dolhan 1987; Farnworth 1990]. All results are quoted for 20°C and ambient pressure. The mass per unit area in grams per square metre and the fabric thickness in millimetres are quoted in the sample description. The mean sample relative humidity is 50% except for samples with hydrophilic films for which the sample relative humidity is quoted after the corresponding water-vapour resistance.

Fabric	Description	Water-Vapour Resistance (mm Still Air Equivalence)
Ripstop Nylon	100% Nylon, uncoated, 92 g/m^2, 0.18 mm	1.7
Nylon	100% Nylon, uncoated, 98 g/m^2, 0.13 mm	2.0
Cotton/Nylon Duck	Cotton/Nylon, 298 g/m^2, 0.711 mm	1.3
Camouflage Goretex	Polyester/Cotton, Gore-tex, hydrophilic top-coat, 0.17 g/m^2, 0.41 mm	26.7 @ 46%, 21.7 @ 52% 13.0 @ 61%, 2.9 @ 88%
Nomex	100% Polyamide, 125 g/m^2, 0.25 mm	0.7
Commander	83% Polyester/17% Cotton, Dermoflex, 207 g/m^2, 0.3 mm	3.8
Amtex	100% Nylon, Dermoflex, 98 g/m^2, 0.22 mm	12.0
Stedthane	100% Nylon, Stedthane, 155 g/m^2, 0.23 mm	43.5 @ 46%, 26.6 @ 51%, 14.3 @ 61, 4.1 @ 84%

conservation laws at the inner and outer wall positions, four equations are obtained: two for heat flow and two for water vapour flow. The equations are coupled both by temperature and by condensation rate. Thus, an iterative procedure must be used. The conditions both inside and outside the tent are treated as given boundary conditions for temperature and relative humidity. Also, it is assumed that there are objects inside the tent which have a surface temperature which is the same as the air temperatures and these objects provide the radiative heat flux to the inner surface. A listing of the computer program used to solve this problem (written in Microsoft QuickBasic) is given in Appendix A.

For the heat flow, the two equations at the inner and outer surfaces respectively are (using the nomenclature in Figure 1):

$$(T_0 - T_1)/R_{t0} + h_{fg}m_{c1} = (T_1 - T_2)/R_{t1} \tag{14}$$

$$(T_1 - T_2)/R_{t1} + h_{fg}m_{c2} = (T_2 - T_3)/R_{t3} \tag{15}$$

and for the mass transport:

$$(P_0 - P_1)/R_{wv0} - m_{c1} = (P_1 - P_2)/R_{wv1} \quad (16)$$

$$(P_1 - P_2)/R_{wv1} - m_{c2} = (P_2 - P_3)/R_{wv3} \quad (17)$$

Initial guesses are made for the two wall surface temperatures and condensation rates. The maximum possible water-vapour transport from the outer surface is calculated from the known boundary conditions and resistances. Using the estimated inner wall temperature, a saturation pressure can be calculated. Using the maximum water-vapour flow, the vapour pressure required between the inside of the tent and the inner wall surface is calculated. If this vapour pressure is greater than the saturation vapour pressure, then it is set equal to the saturation vapour pressure and a new water-vapour flow to the inner wall surface is calculated.

The resulting difference between the water-vapour flow to the inner wall surface and that through the wall appears as condensation. In this model, all of the condensation occurs at the wall while in the real world, some condensation might form in the air before it reaches the wall. A similar procedure is followed to determine conditions at the outer wall surface.

Once new data for condensation rates at the wall surfaces have been obtained, new wall surface temperatures are calculated. If the change for either wall surface temperature is greater than a prescribed tolerance, the above procedure is repeated using the updated surface temperatures and condensation rates until convergence occurs.

3.0 RESULTS

The procedure was run for three nominal fabric samples, three interior conditions and three ambient conditions. The water vapour resistances used are similar to those of ripstop nylon (1 mm of still air equivalent), Dermoflex coated nylon (5 mm of still air equivalent) and Dermoflex coated nylon with a hydrophilic top-coat (NPU23) at a high relative humidity (15 mm of still air equivalent).

The inside tent conditions were selected to represent varying conditions. The most frequently used conditions were 15°C and 100% RH, representing a comfortably warm yet undesirably humid environment such as might occur during meal preparation. A temperature of 5°C and humidity of 100% was selected to represent an uncomfortably cool, humid environment. A temperature of 15°C and humidity of 50% was selected to represent a desirable environment within the tent. The ambient conditions examined were: 0°C and 100% RH; -10°C and 100% RH; -40°C and 100% RH.

Results of the analysis are presented graphically in Figures 2 and 3. The results for the various interior and ambient conditions are plotted against the water-vapour resistance of the wall material. Figure 2 shows the rate of condensation of water vapour at the inside wall surface. Figure 3 shows the transpiration rate from the tent (the rate at which water vapour is leaving the outer wall surface into the ambient air). The results are also included in Table 2.

In all of the test cases, there was no condensation on the outer surface of the wall.

Table 2. Results of Water-Vapour Transport Calculations.

Water Vapour Resistance (mm Still Air)	Interior Conditions Temperature °C	Interior Conditions RH %	Ambient Conditions Temperature °C	Ambient Conditions RH %	Condensation Rate g/m^2s	Transpiration Rate g/m^2s	Fraction of Water Vapour Transported Through Walls
1	15	100	0	100	0.011	0.022	0.70
5	15	100	0	100	0.024	0.0075	0.44
15	15	100	0	100	0.029	0.0028	0.23
1	5	100	0	100	0.0016	0.006	0.72
5	5	100	0	100	0.0053	0.002	0.46
15	5	100	0	100	0.0065	0.0007	0.24
1	15	100	-10	100	0.023	0.027	0.66
5	15	100	-10	100	0.039	0.0089	0.39
15	15	100	-10	100	0.043	0.003	0.20
1	15	50	0	100	0.0	0.0068	0.77
5	15	50	0	100	0.0	0.0042	0.67
15	15	50	0	100	0.0012	0.0018	0.47
1	15	100	-40	100	0.059	0.001	0.07
5	15	100	-40	100	0.0560	0.0009	0.02
15	15	100	-40	100	0.0560	0.0001	0.01

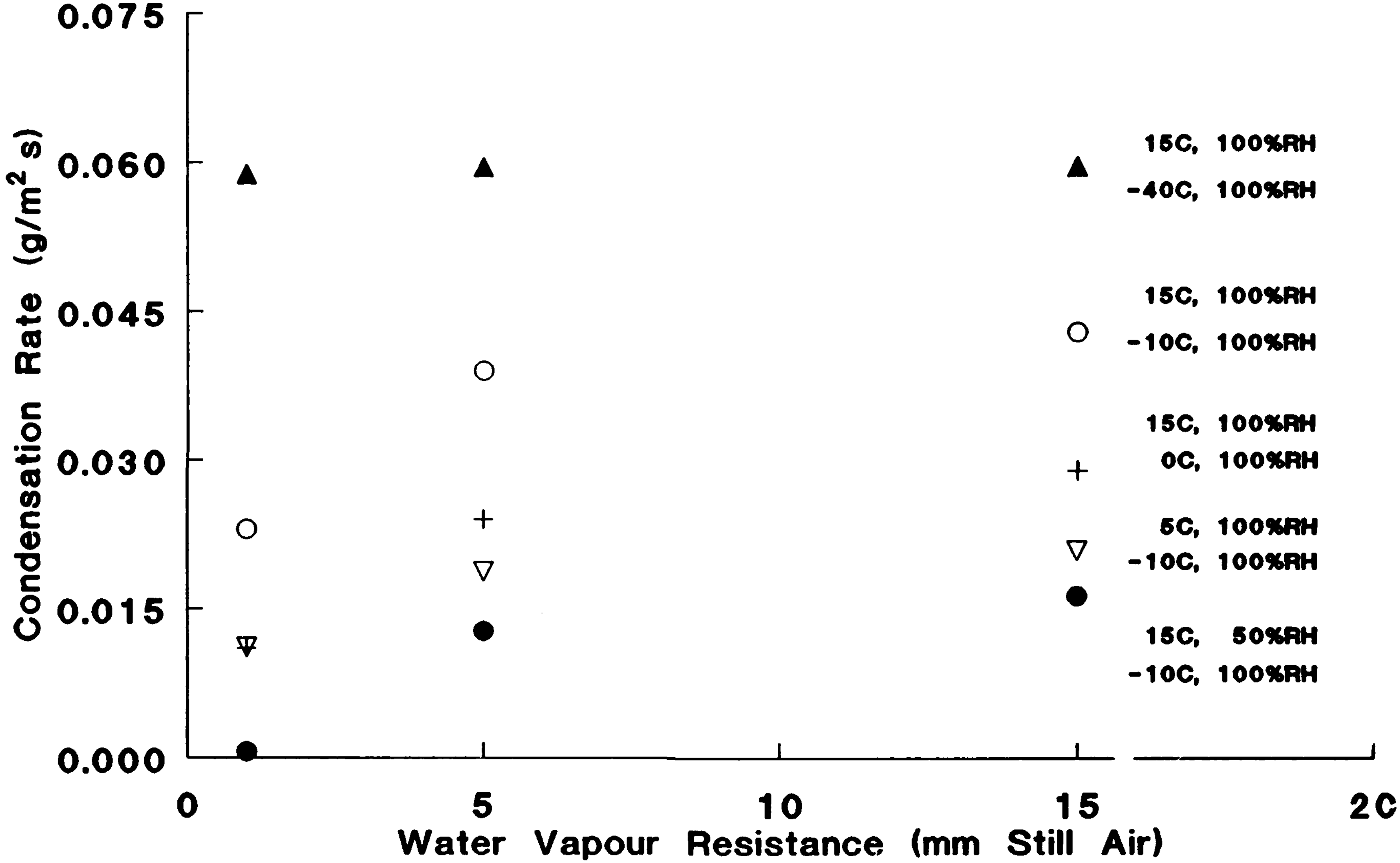

Figure 2. The condensation rate at the inner wall surface is shown as a function of the water-vapour resistance of the wall fabric for various interior and ambient conditions. In each case, the interior air temperature and relative humidity is noted immediately above its corresponding ambient air temperature and relative humidity to the right of the relevant data.

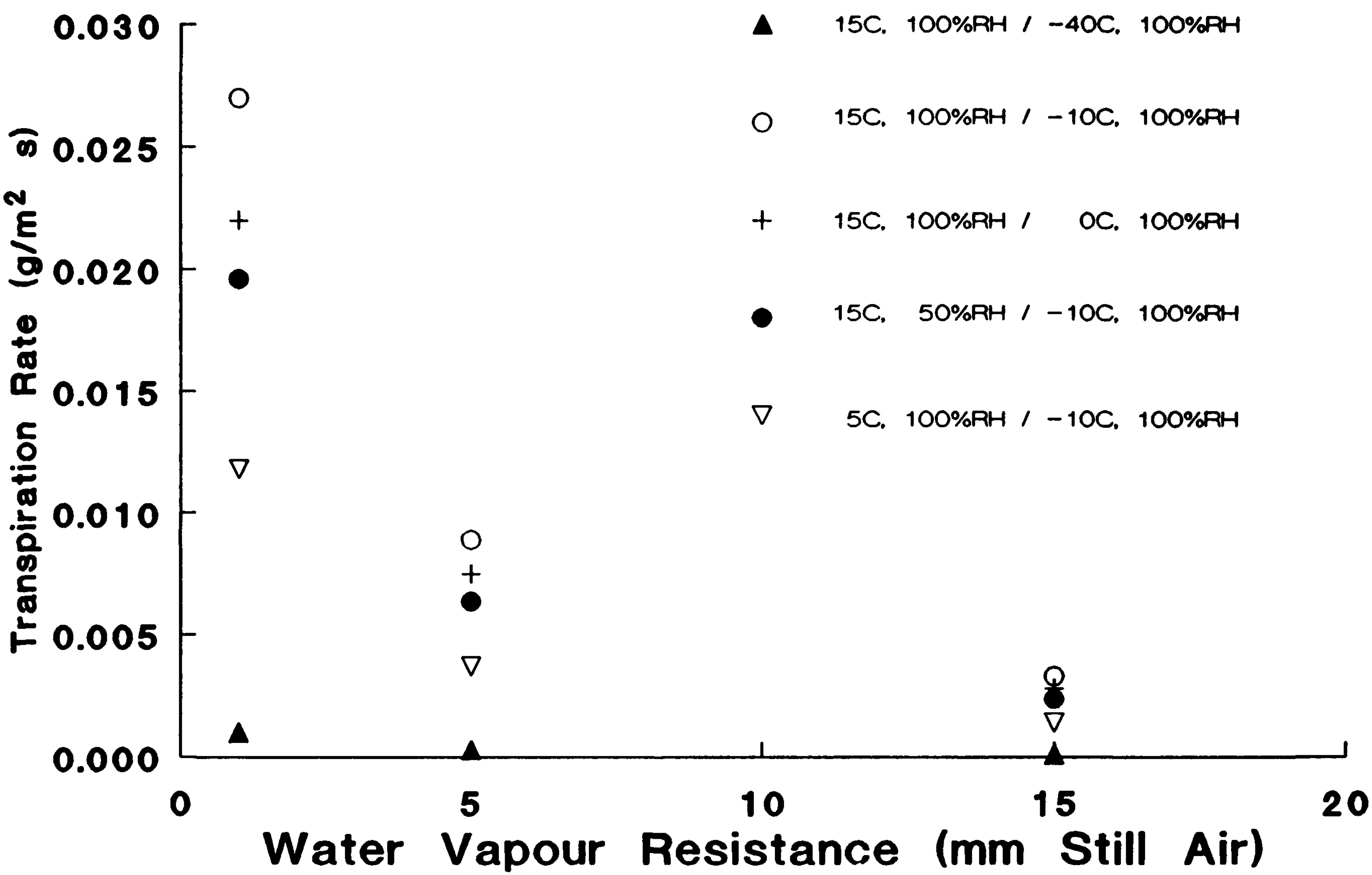

Figure 3. The transpiration rate, or the rate at which water vapour is transported away, from the outer wall surface is shown as a function of the water vapour resistance of the wall fabric for various interior and ambient conditions which are noted in the legend at the upper right of the figure.

4.0 DISCUSSION

Condensation from the warm, humid interior air onto the inner surface of the tent wall was found to be highly dependent upon the interior temperature and humidity, ambient temperature as well as, to a lesser extent, the water-vapour resistance of the wall material (Figure 2).

It can be seen in Figure 2 that decreasing the ambient temperature while holding the interior parameters constant (15°C, 100%RH) results in increasing rates of condensation at the inner wall surface. This is due to the correspondingly lower wall temperature at the inner surface (Figure 4) which results in lower vapour pressure and hence greater drivingpotential for the water-vapour transport to the wall. In general, as the ambient temperaturedecreases the condensation rate increases for all wall materials, however, this is most evident at the lowest water-vapour resistances. At an ambient temperature of -40°C, the water-vapour resistance of the wall has little bearing on the condensation rate as the wall temperature is so low that the vapour pressure difference across the wall is insignificant relative to that across the inner air layer.

Reducing the interior temperature or humidity can result in a significant decrease in the condensation rate as the water-vapour pressure in the air is reduced. This is shown in Figure 2 where the condensation rate at 15°C and 100%RH is used as a baseline for comparisons. By reducing the interior temperature from 15°C to 5°C, both at 100%RH, the condensation rate is halved. Reducing the interior humidity from 100% to 50% (at 15°C) reduces the condensation rate by almost two-thirds.

The condensation rate depends only slightly on the water-vapour resistance of the wall material. The condensation rate is generally lowest at the smallest water-vapour resistance and increases asymptotically to the maximum condensation rate. Once the water-vapour resistance of the wall has reached approximately 5 mm still air, the condensation rate is almost at its maximum.

Figure 3 shows the rate of water-vapour transport from the outer wall, or the transpiration rate, for the various conditions. There is generally a marked decrease in the transpiration rate as the wall water-vapour resistance increases to about 5 mm after which the changes are considerably less. This indicates that modifying of the tent wall, even with a very vapour-permeable film, significantly reduces the rate at which water vapour can diffuse through the wall.

The lowest transpiration rate occurred when the ambient temperature was lowest (-40°C), however, the highest transpiration rate was found to occur when the ambient temperature was at -10°C, not 0°C as one might expect. A calculation was made of the water-vapour flowrate across an arbitrarily thick (1 mm) air layer which had one boundary held at 15°C while the ambient boundary temperature was varied from -40°C to 15°C. The mean water-vapour diffusion resistance, the mass flow rate and the vapour pressure difference across this boundary layer are all plotted as a function of ambient boundary temperature in Figure 5.

From Figure 5, the mean water-vapour resistance of air decreases as the ambient boundary temperature (and hence the mean air-layer temperature) increases. The decrease is not linear, as is evident from equations 7 and 8. The water-vapour pressure difference changes only slightly at low temperatures but increases as the ambient temperature and hence the ambient water-vapour pressure increases. Since the rate of change of the water-vapour diffusion resistance differs from the rate of change of vapour pressure difference and the water-vapour flow rate is a ratio of these two quantities, a maximum occurs in the water-vapour flow rate curve.

To determine whether the amount of water vapour transported out of a tent via the walls is significant, an estimate of the total water-vapour transport from the tent was made. Representative values where selected based on the ventilation and tent size requirements per man in a tent heated with gasoline stoves and the only avenues for water-vapour transport from the tent were assumed to be by ventilation and through the walls. It was assumed that each man in a tent required: 5 l/s of ventilation; 4.5 m^2 of tent wall and roof area. These results are shown in Figure 6 where it can be seen that a substantial portion of the water vapour in the tent escapes through the walls in all but the coldest environments.

The results indicate that the water-vapour transport through an very permeable fabric wall (1 mm still air water-vapour resistance) in a cold wet environment can account for approximately 75% of the water-vapour lost from the tent. As the water-vapour resistance of the fabric increases, the fraction of water vapour lost from the tent through the tent walls decreases markedly, although, a fabric with a water-vapour resistance can still account for approximately 25% of the water-vapour loss. As the temperature drops well below freezing, the fraction of water vapour which is lost through the tent wall is insignificant even for the uncoated fabric with the lowest water-vapour resistance.

All of the discussion has so far considered only a single wall tent. Many tents make use of a fly-sheet covering much of the outer surface and tents for cold weather often include a liner. The analysis used in this study could be extended to include these variations, however, some general, qualitative predictions may be made with reasonable confidence without a more complete analysis.

Both a fly-sheet and a liner provide additional thermal insulation and water-vapour diffusion resistance between the interior of the tent and the ambient air. The fly-sheet adds these resistances onto the outside of the tent wall, so that the tent wall will be warmer permitting proportionally more water vapour to pass through the tent wall with less condensing on the inner tent wall surface. Much of the water vapour which passes through the tent wall will undoubtably then condense on the fly-sheet. If the condensate on the fly-sheet can be removed from the fly-sheet when the tent is struck, it is of little consequence but that which remains will increase the weight of the tent ensemble.

A liner added to the inside of a tent will produce the opposite result, making the tent wall colder and hence less water vapour will pass through the tent wall to the ambient air. This means that more water vapour will condense inside the tent increasing both the tent weight and the packed volume (due to increased fabric stiffness as the water freezes in cold climates).

Use of a coated fabric such as Dermoflex or Gortex for the tent wall and roof may allow the use of the tent without a fly, thereby saving weight. For example, a commercial 5-Man tent typically has approximately 23 m^2 of upper surface area and the complete tents weighs approximately 9 kg. Assuming a tent wall material weighing 100 g/m^2 and a impermeable fly weighing 100 g/m^2, the weight of the fabric is approximately 4.5 kg. If the tent wall material was replaced by a coated, water-vapour permeable fabric with a weight of 150 g/m^2 and the fly dispensed with, 1.125 kg could be saved which represents 13% of the total tent weight.

A fly does, however, have uses other than protecting the tent from the weather, especially for military applications. A fly acts as a sacrificial layer, protecting the more expensive tent from photo-degradation. The fly can add thermal insulation to the tent, thereby maintaining a more comfortable environment with higher heating-fuel economy. The fly can also provide camouflage, both visual and infra-red, which can be easily changed to meet the requirements of differing theatres of operation.

An additional caveat should also be made concerning the use of coated and laminated fabrics in tents. Many of these materials have significant resistance to the diffusion of gases [Osczevski 1990], especially the continuous hydrophilic films. This could conceivably lead to unhealthy and dangerously high levels of carbon monoxide and carbon dioxide along with very low levels of oxygen if ventilation of the tent is restricted. Care must be taken to ensure adequate ventilation through the tent vents even when stoves are not on as even breathing will eventually significantly deplete the oxygen levels within the tent.

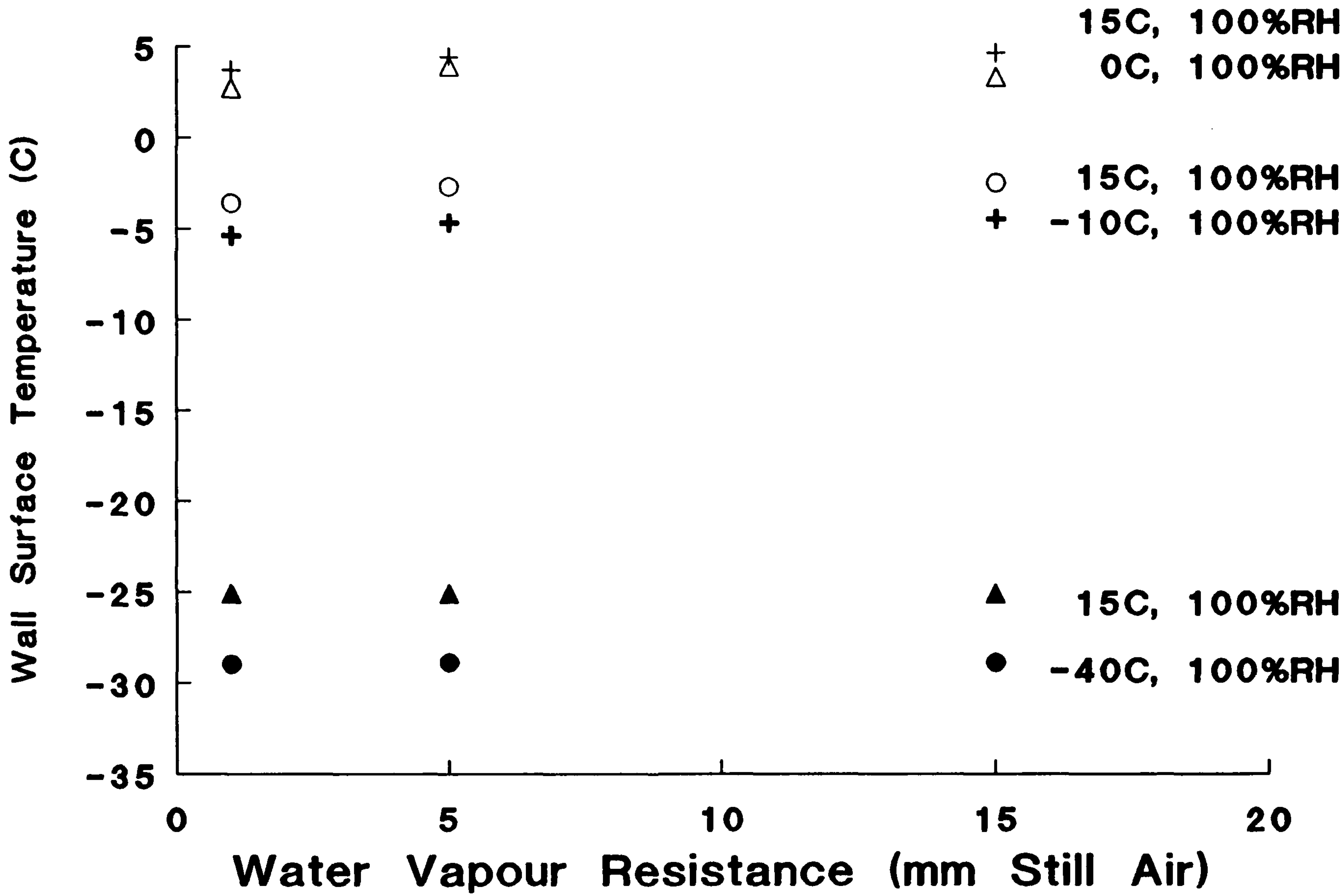

Figure 4. The inner (warmer) and outer wall surface temperatures are shown as a function of the wall water-vapour resistance (and hence the condensation rate) for the same interior conditions with three different ambient temperatures as noted at the right of the figure.

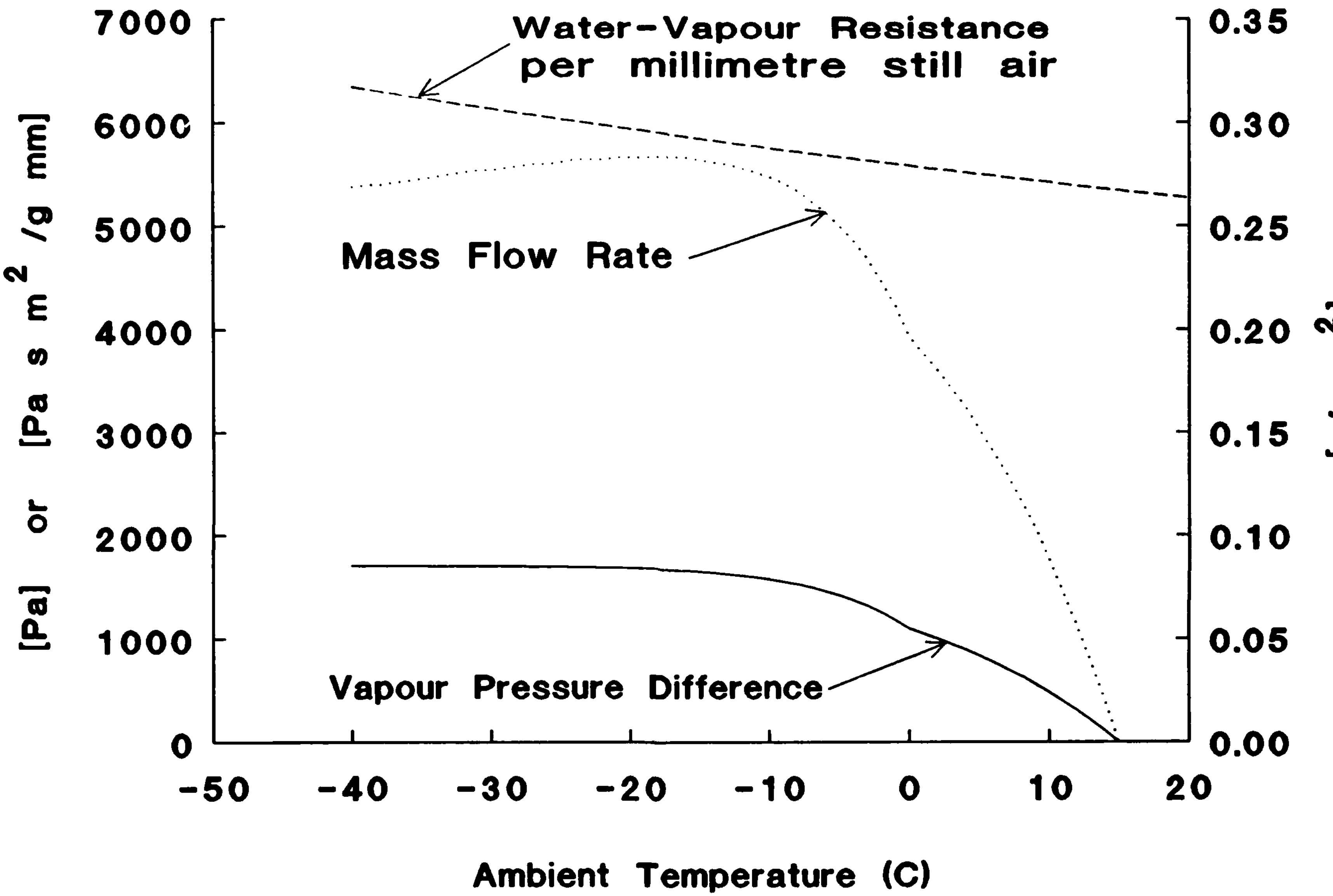

Figure 5. The vapour pressure difference between a reference temperature of 15°C and the ambient temperature and the water-vapour resistance per unit thickness of still air are plotted as functions of the ambient temperature against the left axis. The mass flow rate of water-vapour across a 1 mm thick still air layer is also shown against the right axis.

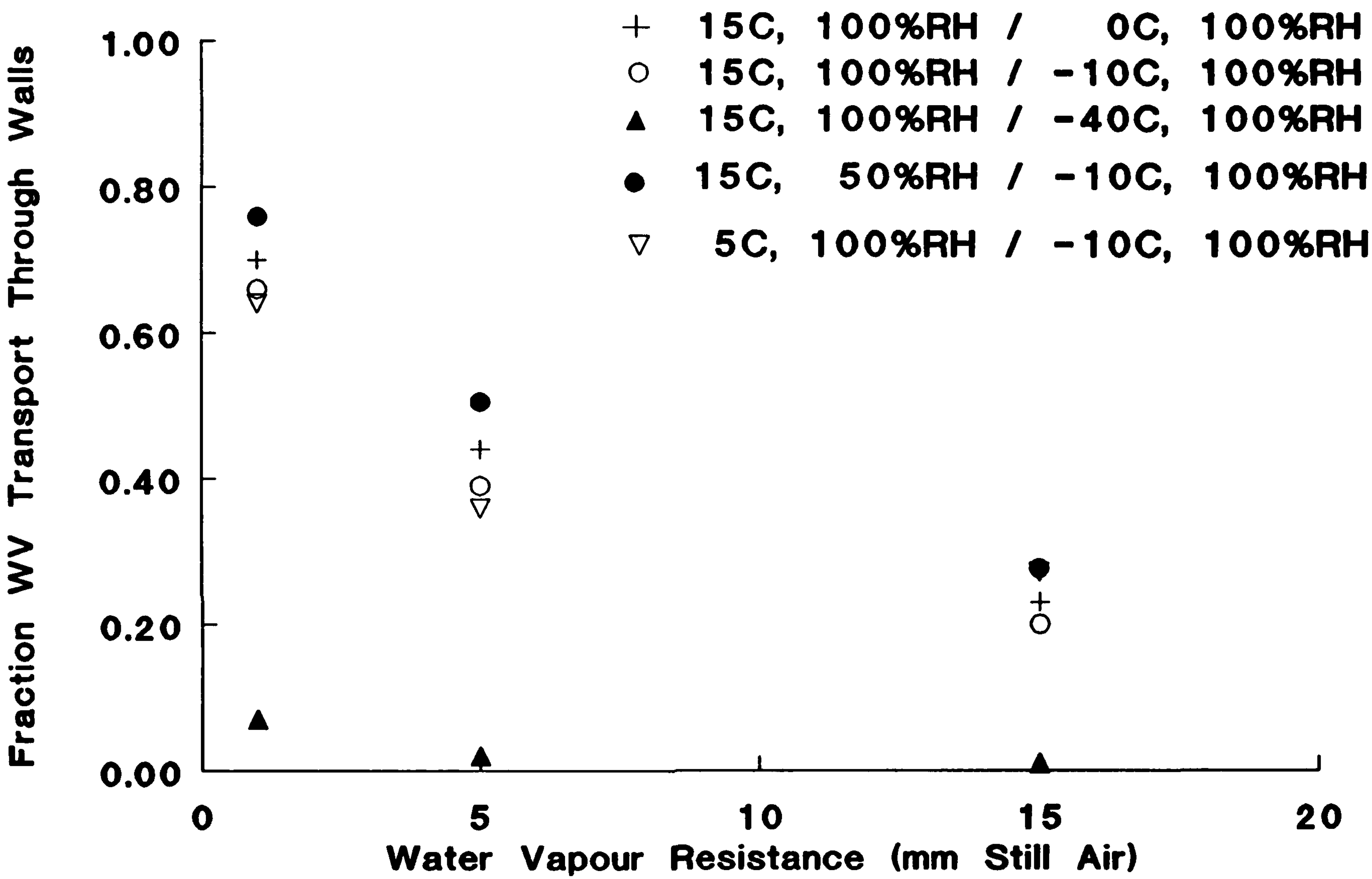

Figure 6. The calculated fraction of water vapour transferred from the tent interior through the tent walls is shown as a function of the water -vapour resistance of the wall fabric for various ambient conditions as noted in the upper right legend. This calculation is based on estimated values of tent size and ventilation rate which are assumed representative for personnel tents heated by gasoline stoves.

5.0 CONCLUSION

In general, vapour-permeable, water-proof fabrics can be used for tents so that a fly-sheet is unnecessary, thereby reducing the overall weight of the tent. Since these fabrics generally have higher water-vapour diffusion resistance than uncoated fabrics, their use will increase the amount of condensation on the inside tent wall over similar tents of uncoated fabrics in most cases.

Since many water-proof, vapour permeable fabrics have significant resistance to the diffusion of air, care must be taken to select materials which do permit diffusion. The user must be made aware of the potential hazards which may arise unless adequate ventilation is maintained.

Elimination of the fly-sheet does present some other problems, especially for military applications. Degradation of the tent materials due to solar radiation may occur more quickly and the degree of camouflage against visible and infra-red radiation will be reduced in many situations.

In conclusion, the designer and the user must decide whether advantages of a vapour-permeable, water-proof tent without a fly-sheet over a conventional fabric tent with an impermeable fly-sheet are greater than the disadvantages. The savings in weight achieved by eliminating the fly-sheet must be evaluated against the disadvantages such as increased condensation within the tent, shorter material life-span, lower thermal insulation and reduced camouflage capability.

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Appendix A. Program Listing.

```
'
'   WVtent - a program to calculate the water vapour transport out
'           of a tent.  For the present, the analysis is limited
'           to fully saturated, steady-state cases.
'
'
' mw = mass flow rate of h2o through the wall
' mv = mass flow rate of h2o through the vents
' n = size of tent in "numbers of men"
' gamma = absolute humidity, kg/kg-air
' rh() = relative humidity
' v = volume flow rate of air, l/s/man
' a = tent surface area, m^2/man
' rt() = thermal resistance, m^2.K/W
' rwv() = water-vapour resistance, Pa.m^2.s/g
' p() = water-vapour pressure, Pa
' t() = temperature, C
' tg() = temperature estimates, C
' tr() = temperature of a thermal resistance layer, C
' lt() = thickness of a thermal resistance layer, m
' k() = thermal stiffness matrix
' f() = thermal force matrix
' deltat() = temperature difference between old and new wall temp estimates
'
' Subscripts
' 0 = inside conditions
' 1 = inside wall surface (or average wall condition)
' 2 = outside wall surface
' 3 = ambient conditions
'
DEFDBL A-H, P-Z
DIM t(0 TO 3), rh(0 TO 3), tg(1 TO 2), tr(0 TO 3), rt(0 TO 3), rwv(0 TO 3)
DIM deltat(1 TO 2), p(0 TO 3), lt(0 TO 3), k(2, 2), f(2), mt(0 TO 3)
DIM pg(1 TO 2), mc(1 TO 2)
DEFSNG I-O
'
DECLARE FUNCTION dens# (t#)
DECLARE FUNCTION dwv# (t#)
DECLARE FUNCTION humid# (t#, rh#)
DECLARE FUNCTION pwv# (t#)
DECLARE FUNCTION rthermal# (t#, l)
'
'
'Define the ^C key (Control-C) bail-out of the computation
'KEY 15, CHR$(3)
'ON KEY(15) GOSUB stopcomp
'KEY(15) ON
'
'
OPEN "d:\work\wvtent.dat" FOR OUTPUT AS #1
```

```
'
'Assumed Constants
vol = 5        'l/s        enough for half of a 1500W stove and 1 man
a = 4.5        'm^2/man      typical tent surface area per man
rgas = 8.314  'N.m/gmole.K  Universal Gas Constant
mh2o = 18      'g/gmole      Molecular Weight of water vapour
lt(0) = .005   'm            inner still air layer thickness
lt(3) = .0005  'm            outer still air layer thickness,
lt(1) = .0003  'm            Actual Wall Thickness
hfg = 2475     'J/g          Enthalpy of evaporation/condensation (10C)
'
'
Begin:
'
CLS
INPUT "How many men"; n
v = n * vol / 1000' m^3/s
area = n * a
PRINT
PRINT
INPUT "Mean Inside Temperature"; t(0)
INPUT "Mean Inside Relative Humidity, 0 to 1"; rh(0)
PRINT
INPUT "Mean Outside Temperature"; t(3)
INPUT "Mean Outside Relative Humidity, 0 to 1"; rh(3)
PRINT
PRINT
INPUT "Wall Water Vapour Resistance in mm Still Air"; lvw
lvw = lvw / 1000' Change from mm to metres
PRINT
PRINT
PRINT , "Please Stand By,  Computation in progress."
PRINT
'
CLS
'
'Initial guesses for the wall temperatures
tg(1) = .55 * (t(0) + t(3))
tg(2) = .45 * (t(0) + t(3))
'
'Counter to eliminate runaway for non-converging analysis
i = 1
'
'
'Iterate on the wall temperatures and wv flows
'
DO
'
PRINT , "Iteration Number"; i
'
'Calculate a mean temp of layers for thermal resistance calculations
tr(0) = (t(0) + tg(1)) / 2
```

```
tr(3) = (t(3) + tg(2)) / 2
tr(1) = (tg(1) + tg(2)) / 2
'
'Calculate the various thermal resistances  (m^2.K/W)
rt(0) = rthermal(tr(0), lt(0))  'Inner Boundary Layer
rt(3) = rthermal(tr(3), lt(3))  'Outer Boundary Layer
rt(1) = lt(1) / .04             'Fabric Intrinsic Thermal Resistance
'
'
'Calculate the various water vapour resistances  (Pa.m^2.s/g)
rwv(0) = lt(0) * rgas * (tr(0) + 273.16) / (mh2o * dwv(tr(0)) * 10 ^ -4)
rwv(3) = lt(3) * rgas * (tr(3) + 273.16) / (mh2o * dwv(tr(3)) * 10 ^ -4)
rwv(1) = lvw * rgas * (tr(1) + 273.16) / (mh2o * dwv(tr(1)) * 10 ^ -4)
'
'
'Calculate the saturation vapour pressures at each point  (Pa)
p(0) = pwv(t(0))
p(1) = pwv(tg(1))
p(2) = pwv(tg(2))
p(3) = pwv(t(3))
'
'
'Calculate the maximum wv flow rate given no condensation  (g/m^2.s)
mtmax = (rh(0) * p(0) - rh(3) * p(3)) / (rwv(0) + rwv(1) + rwv(3))
'
'Calculate an initial guess for the inside wall surface wv pressure
pg(1) = rh(0) * p(0) - mtmax * rwv(0)
'
IF pg(1) > p(1) THEN            'condensation occurs at the inner wall
'
  rh(1) = 1
  mt(1) = (rh(1) * p(1) - rh(3) * p(3)) / (rwv(1) + rwv(3))  'bl flow
  mt(0) = (rh(0) * p(0) - rh(1) * p(1)) / rwv(0)             'wall flow
  mc(1) = mt(0) - mt(1)                                      'condensed
'
' Calculate an initial guess for the outer wall surface wv pressure
  pg(2) = rh(1) * p(1) - mt(1) * rwv(1)
'
  IF pg(2) > p(2) THEN          'condensation occurs at the outer wall
'
    rh(2) = 1
    mt(3) = (rh(2) * p(2) - rh(3) * p(3)) / rwv(3)  'outer bl flow
    mc(2) = mt(1) - mt(3)                           'condensed
'
  ELSEIF pg(2) <= p(2) THEN   'no condensation occurs at the outer wall
'
    rh(2) = pg(2) / p(2)
    mc(2) = 0
    mt(3) = (rh(2) * p(2) - rh(3) * p(3)) / rwv(3) 'outer bl flow
'
  END IF
'
```

```
ELSEIF pg(1) <= p(1) THEN      'no condensation occurs at the inner wall
'
  mc(1) = 0
  rh(1) = pg(1) / p(1)
  mt(0) = (rh(0) * p(0) - rh(1) * p(1)) / rwv(0)
  mt(1) = mt(0)
'
  pg(2) = rh(1) * p(1) - mt(1) * rwv(1)
'
  IF pg(2) > p(2) THEN        'condensation occurs at the outer wall
'
    rh(2) = 1
    mt(3) = (rh(2) * p(2) - rh(3) * p(3)) / rwv(3)
    mc(2) = mt(1) - mt(3)
'
  ELSEIF pg(2) <= p(2) THEN   'no condensation occurs at the outer wall
'
    rh(2) = pg(2) / p(2)
    mc(2) = 0
    mt(3) = (rh(2) * p(2) - rh(3) * p(3)) / rwv(3)
'
  END IF
END IF
'
'
'Calculate the components of the thermal stiffness matrix and force vector
k(1, 1) = rt(1) + rt(0)
k(1, 2) = -rt(0)
k(2, 1) = -rt(3)
k(2, 2) = rt(3) + rt(1)
'
f(1) = rt(1) * rt(0) * hfg * mc(1) + rt(1) * t(0)
f(2) = rt(3) * rt(1) * hfg * mc(2) + rt(1) * t(3)
'
'
'Calculate the new outer and inner wall surface temperatures
t(2) = (k(2, 1) * f(1) - k(1, 1) * f(2)) / (k(2, 1) * k(1, 2) - k(1, 1) * k(2, 2))
t(1) = (k(2, 2) * f(1) - k(1, 2) * f(2)) / (k(2, 2) * k(1, 1) - k(1, 2) * k(2, 1))
'
'Calculate the convergence criteria
deltat(1) = tg(1) - t(1)
deltat(2) = tg(2) - t(2)
'
'Update the wall temperature guesses in case convergence is incomplete
tg(1) = tg(1) - deltat(1) / 2
tg(2) = tg(2) - deltat(2) / 2
'
'
'Catch-all in case of divergence or slow convergence
IF i = 100 THEN
  PRINT #1, i; " iterations with no convergence."
  PRINT #1, "Deltat(1) = "; deltat(1)
```

```
  PRINT #1, "Deltat(2) = "; deltat(2)
  GOTO endloop
END IF
'
i = i + 1
'
LOOP WHILE ABS(deltat(1)) > .001 OR ABS(deltat(2)) > .001
'
endloop:
'
gamma(0) = humid(t(0), rh(0))  'Humidity ratios
gamma(3) = humid(t(3), rh(3))
'
'Calculate the amount of wv vented from the assumed tent
mv = v * dens(t(0)) * (gamma(0) - gamma(3)) * 1000' g/s
'
mt = mv + area * mt(3)          ' g/s  total wv transport from tent
mperw = area * mt(3) / mt  'fraction of water vapour transfered through walls
mperv = mv / mt            '  "    "  "    "    "       "    vents
'
'
ff$ = CHR$(12)  '  Form Feed Character
PRINT #1,
PRINT #1, "Calculations of Water Vapour Transport from a tent for:"
PRINT #1, "-----------------------------------------------------"
PRINT #1,
PRINT #1, "Number of men: "; n
PRINT #1, "Number of 1500W stoves: "; n / 2
PRINT #1, "Tent Surface Area: "; area; " m^2"
PRINT #1, "Ventilation Rate: "; v; " m^3/s"
PRINT #1,
PRINT #1, "Inside Temperature: "; t(0); "C and Relative Humidity: "; rh(0)
PRINT #1, "Ambient Temperature: "; t(3); "C and Relative Humidity: "; rh(3)
PRINT #1, "Inner Wall Surface Temperature: "; t(1); " C and RH: "; rh(1)
PRINT #1, "Outer Wall Surface Temperature: "; t(2); " C and RH: "; rh(2)
PRINT #1,
PRINT #1, "Inside absolute humidity:  "; gamma(0); " kg/kg-air"
PRINT #1, "Ambient absolute humidity: "; gamma(3)
PRINT #1,
PRINT #1, "Inner Still Air Layer Thickness: "; lt(0) * 1000; " mm"
PRINT #1, "Outer Still Air Layer Thickness: "; lt(3) * 1000; " mm"
PRINT #1, "WV Resistance Equivalent Still Air Of Wall: "; lvw * 1000; " mm"
PRINT #1,
PRINT #1, "Inner boundary layer thermal resistance: "; rt(0); "m^2.K/W"
PRINT #1, "Outer boundary layer thermal resistance: "; rt(3)
PRINT #1, "Fabric thermal resistance: "; rt(1)
PRINT #1,
PRINT #1, "Inner boundary layer wv resistance: "; rwv(0); " Pa.m^2.s/g"
PRINT #1, "Outer boundary layer wv resistance: "; rwv(3)
PRINT #1, "Fabric wv resistance: "; rwv(1)
PRINT #1,
PRINT #1, "Inside saturation vapour pressure: "; p(0); " Pa"
```

```
PRINT #1, "Inner Wall saturation vapour pressure: "; p(1)
PRINT #1, "Outer Wall saturation vapour pressure: "; p(2)
PRINT #1, "Ambient Vapour pressure: "; p(3)
PRINT #1,
PRINT #1, "Water vapour transport to the inside wall: "; mt(0); " g/m^2.s"
PRINT #1, "Water vapour transport through the wall: "; mt(1); " g/m^2.s"
PRINT #1, "Water vapour transport from the outside wall: "; mt(3); " g/m^2.s"
PRINT #1, "Water vapour condensed on inside wall:   "; mc(1); " g/m^2.s"
PRINT #1, "Water vapour condensed on outside wall:  "; mc(2); " g/m^2.s"
PRINT #1,
PRINT #1,
PRINT #1, "For this specific tent:"
PRINT #1, "----------------------"
PRINT #1, "Water Vapour Transport Through Walls:      "; mt(1) * area; " g/s     "; mperw * 100; "%"
PRINT #1, "Water Vapour Transport Through Vents:      "; mv; " g/s     "; mperv * 100; "%"
PRINT #1, "Water Vapour Condensed On Inside Wall:     "; mc(1) * area; " g/s "
PRINT #1, "Water Vapour Condensed On Outside Wall:    "; mc(2) * area; " g/s "
PRINT #1,
PRINT #1, "Total Water Vapour Transport out of tent: "; mt; " g/s"
'
PRINT #1,
PRINT #1, ff$
PRINT
INPUT ; "Do you wish to do another case"; yn$
IF yn$ = "Y" OR yn$ = "y" THEN GOTO Begin
'
GOTO stopp:
'
stopcomp:
CLS
PRINT
PRINT
PRINT , "Program halted at your request."
PRINT , "Press any key to return to editing."
PRINT
'
stopp:
STOP



DEFSNG A-H, P-Z
FUNCTION dens# (t#)
'
'This function calculates the density of dry air assuming it can be
'adequately represented as an ideal gas.
't = gas temperature, C
'dens = gas density, kg/m^3
DEFDBL A-Z
    dens = 352.989 / (t + 273.16)
END FUNCTION
```

```
FUNCTION dwv# (t#)
'
'This function calculates the water vapour diffusivity in air.
'Pressure dependence has been ignored.
'
't = air temperature, C
'dwv = diffusivity, cm^2/s
'
'
DEFDBL A-Z
d0 = .226 'cm^2/s  reference diffusivity at 0C
t0 = 273.16 'C     reference temperature
n = 1.81 'temperature ratio dependence exponent
'
dwv = d0 * ((273.16 + t) / t0) ^ n
'
END FUNCTION



FUNCTION humid# (t#, rh#)
'
'This function calculates the Humidity Ratio at the specified temperature
'and relative humidity assuming the air and water vapour can be characterized
'as ideal gases.
'
'p = total pressure
'pw = water vapour pressure
'pa = dry air pressure
'humid = humidity ration in (mass of water)/(mass of dry air)
'
DEFDBL A-Z
'
rair = 278.06 'N.m/kg.K   gas constant for air
'                      (8.314 N.m/gmole.K)/(29.9 g/gmole)*(1000 g/kg)
   pw = rh * pwv(t) 'Pa
'
   pa = dens(t) * rair * (t + 273.16) 'Pa
'
   humid = .62198 * pw / pa
'
END FUNCTION



FUNCTION pwv# (t#)
'   This function calculates the saturation water vapour pressure in
'   Pascals given the ambient temperature in degrees Celcius.
'
DEFDBL A-Z
DIM f(8)
```

```
'
IF t >= 0 THEN
'
'       Vapour Pressure over liquid water:  0C <= t <= 374C
'
'Constants from the Goff Formulas, ASHREA Fundamentals Handbook
f(1) = -741.9242
f(2) = -29.721
f(3) = -11.55286
f(4) = -.868564
f(5) = .1094098
f(6) = .439993
f(7) = .2520658
f(8) = .0521868
'
sum = 0
'
FOR i = 1 TO 8
  sum = sum + f(i) * (.65 - .01 * t) ^ (i - 1)
'
NEXT i
'
  temp = .01 * (374.136 - t) * sum / (t + 273.16)
  pwv = (1.0132 * 10 ^ 5) * 217.99 * EXP(temp)  'Pa
'
ELSEIF t < 0 THEN
'
'       Vapour Pressure over ice:  -100C <= t <= 0C
'
  theta = 273.16 / (t + 273.16)
  temp = -9.096936 * (1 - theta) - 1.5489 * LOG(theta)
  temp = temp + (1.50474 * 10 ^ -4) * (1 - 10 ^ -8.29692 * (1 / theta - 1))
  temp = temp + (.42873 * 10 ^ -3) * (10 ^ 4.76955 * (1 - theta) - 1) - 2.2195983#
'
  pwv = (1.0132 * 10 ^ 5) * EXP(temp / .43429) 'Pa
'
END IF
END FUNCTION



FUNCTION rthermal# (t#, l)
'
'This function calculates the resistance of a still air layer to both
' conductive and radiative heat transfer
'
DEFSNG I-O
'
sigma = 5.67 * 10 ^ -8          'W/m^2 K^4   Stephan-Boltsman Constant
ka = .024 + t * 7 * 10 ^ -5      'W/mK        Thermal Conductivity of air
hc = ka / l                     'W/m^2 K     Conductive Heat Transfer Coef
```

```
hr = 4 * sigma * (t + 273.16) ^ 3  'W/m^2 K     Radiative Heat Transfer Coef
ht = hc + hr                       'W/m^2 K     Total Heat Transfer Coef
'
rthermal = 1 / ht                  'm^2 K/W     Thermal Resistance
'
END FUNCTION
```

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The usefulness of a tent used in cold weather depends upon, among other things, the condensation of water vapour on the tent walls as this condensate can wet occupants' insulating garments, increase the tent weight and increase the tent's packed volume. In this report, the heat and moisture transport across a single fabric layer as might occur in a tent is studied by means of a simple, numerical model. The effects of water-vapour permeability of the fabric, interior air temperature and relative humidity and the ambient temperature on the condensation rate within the tent are examined. It was found that small decreases in the water-vapour permeability of the fabric layer can result in large increases in the condensation rate at the wall. Reducing the interior tent temperature or relative humidity can significantly reduce the condensation rate. The results indicate that a substantial portion of the water vapour within a very humid tent atmosphere escapes through the tent walls in all but the coldest ambient conditions for fabrics with low water-vapour resistance. A discussion is made regarding some of the advantages and disadvantages of using a single vapour permeable, waterproof fabric in place of more conventional arrangements with a permeable tent wall covered with an impermeable fly-sheet.

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Water
Vapour
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Heat
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